EFFECTS OF FREESTREAM TURBULENCE ON TURBINE BLADE HEAT TRANSFER

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Experiments have shown that moderate turbulence levels can nearly double turbine blade stagnation region heat transfer. Data have also shown that turbine blade heat transfer is strongly affected by the scale of turbulence as well as its level. In addition to the stagnation region, turbulence is often seen to increase pressure surface heat transfer. This is especially evident at low to moderate Reynolds numbers. Vane and rotor stagnation region, and vane pressure surface heat transfer augmentation is often seen in a pre-transition environment. Rotor pressure surface augmentation is often seen in a relaminarized post-transition environment. Accurate predictions of transition and relaminarization are critical to accurately predicting blade surface heat transfer. An approach is described which incorporates the effects of both turbulence level and scale into a CFD analysis.The model for the effects of turbulence intensity and scale is derived from experimental data for cylindrical and elliptical leading edges. Results using this model are compared with experimental data for both vane and rotor geometries. There is a twofold purpose to these comparisons. One is to illustrate that using a model which includes the effects of turbulence length scale improves agreement with data. The second is to illustrate where improvements in the modeling are needed.

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Objectives

- Account for Turbulence level and length scale on turbine blade heat transfer
- Compare measured and predicted vane & rotor blade heat transfer
- Compare predictions with and without models to account for freestream turbulence effects
- Identify areas where modeling improvements are needed

Models Examined

1) No Augmentation
2) Smith & Kuethe – No length scale effect
3) Smith & Kuethe + Van Fossen – Length scale modeled using Leading edge data
4) Ames model with Leading edge term
5) Ames model without Leading edge term

Vanes

Name	Re_2 X10^{-6}	Tu,%	L/C	Description
Ames	0.5 - 0.8	1-20	0.08-0.3	M_2=0.17 - 0.27
Ames	0.5 - 2.0	1-20	0.07-0.23	Incompressible
Thole	0.5 & 1.1	1-20	0.08	Incompressible
Arts	0.5 - 2.0	1-6	> 0.05	Transonic

Rotors

Name	Re_2 X10^{-6}	Tu, %	L/C	Description
Giel-1	0.5 - 0.87	13	0.17	M_2=0.56 - 0.8
Giel-2	0.4 - 3.8	13	0.17	M_2=0.33 - 0.9
Arts	0.6 – 2.3	1-6	> 0.04	Transonic

Calculation procedure

- 2D Navier-Stokes (RVCQ3D) – Primarily concerned with leading edge and pressure side
- Two layer algebraic turbulence model
- Freestream turbulence effects serve to augment laminar viscosity
- No augmentation when flow is turbulent
- Length scale constant – No variation in length with flow acceleration or deceleration

Turbulence Augmentation Models

Smith and Kuethe model

$$\nu_{Tu} / \nu_{Lam} = C_{SK} Tu U y$$

$$C_{SK} = 0.164$$

Smith & Kuethe + Van Fossen’s Leading edge model

$$\nu_{Tu} / \nu_{Lam} = 0.3 C_{SK} Tu U y \, (D_{LE} / L)^{1/3}$$

Ames – No Leading Edge effect

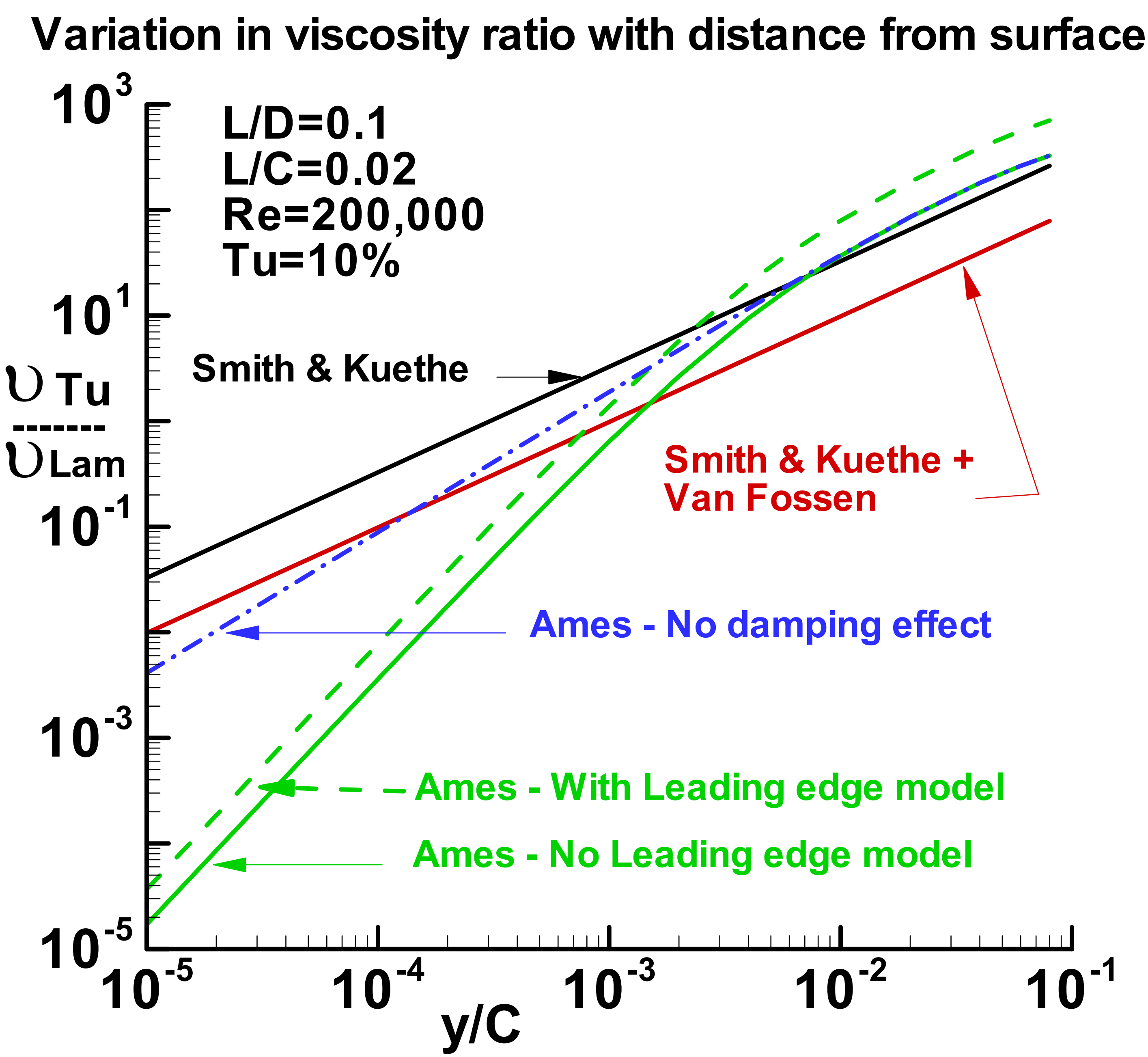
$$\nu_{Tu} = 0.135 \; Tu \, U \, L \left[1 - \exp\left(\frac{-2.9\, y}{L} \right) \right]^{4/3} D_\nu$$

$$D_\nu = 1 - \exp\left(-0.15\, y \middle/ \left(\frac{L\, \nu^3}{1.5 \left| u' \right|^3} \right)^{1/4} \right)$$

Ames – With Leading Edge effect

$$\nu^*_{Tu} / \nu_{Tu} = 1 + \left(\left(Re_D / 4 \right)^{1/12} - 1 \right) \times f_{amp}$$

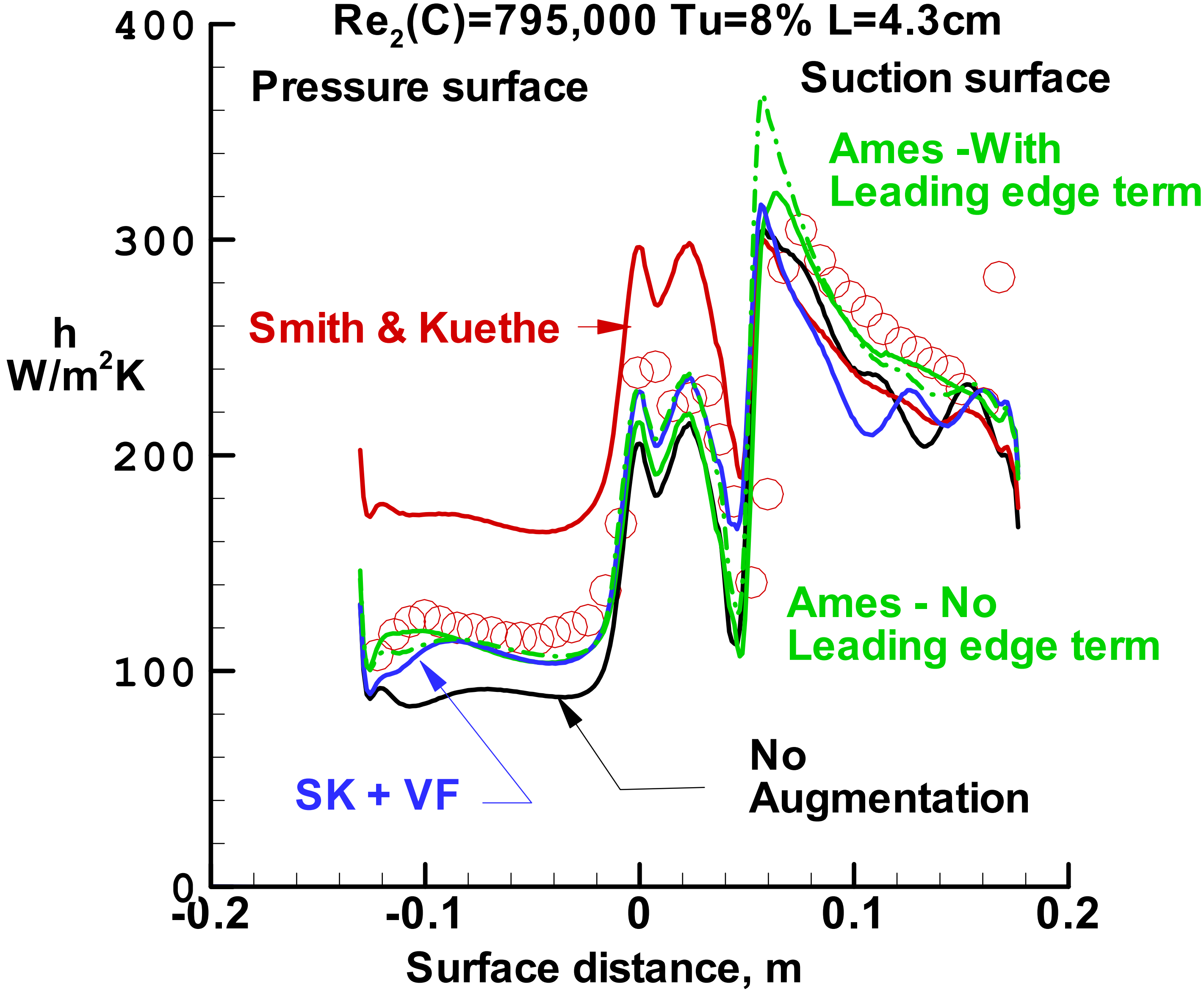
$$f_{amp} = 1 - \exp\left\{ -2.5 \left[\frac{dU\,(S)/ds}{dU\,(S=0)/ds} \right]^2 \right\}$$

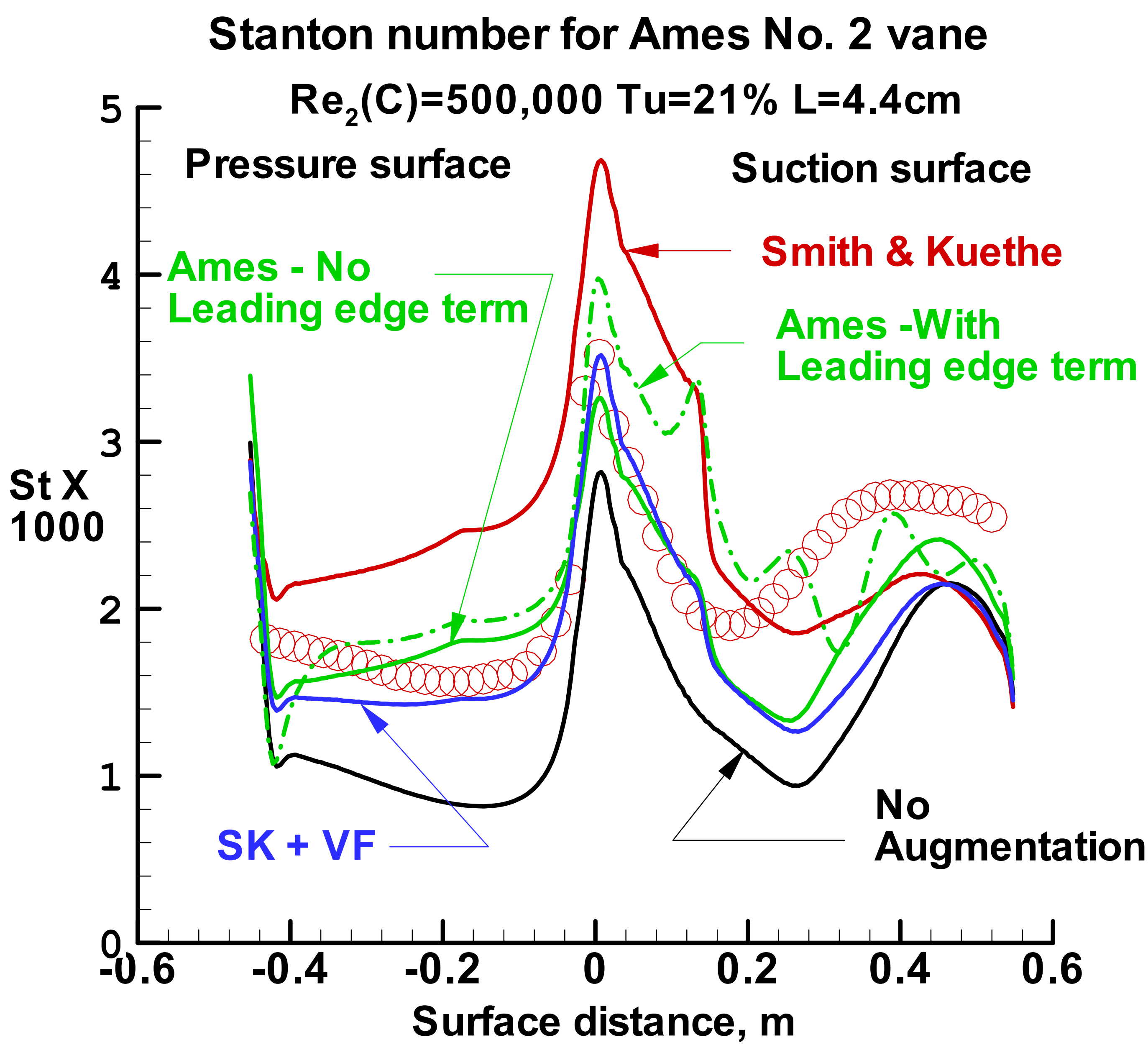


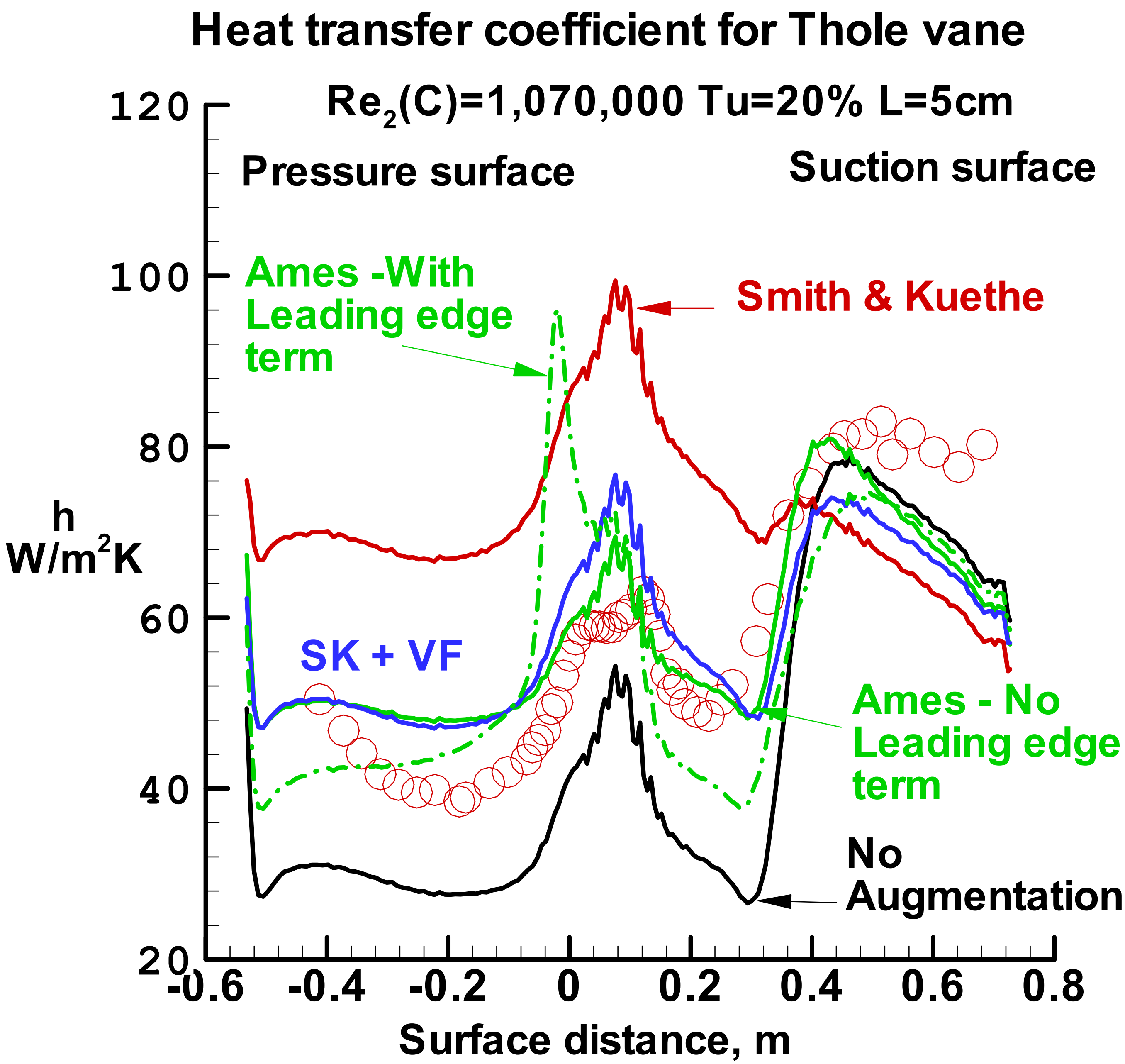
Variation in viscosity ratio with distance from surface
L/D=0.1
L/C=0.02
Re=200,000
Tu=10%
Smith & Kuethe
Smith & Kuethe +
Van Fossen
Ames - No damping effect
Ames - With Leading edge model
Ames - No Leading edge model
υ Tu

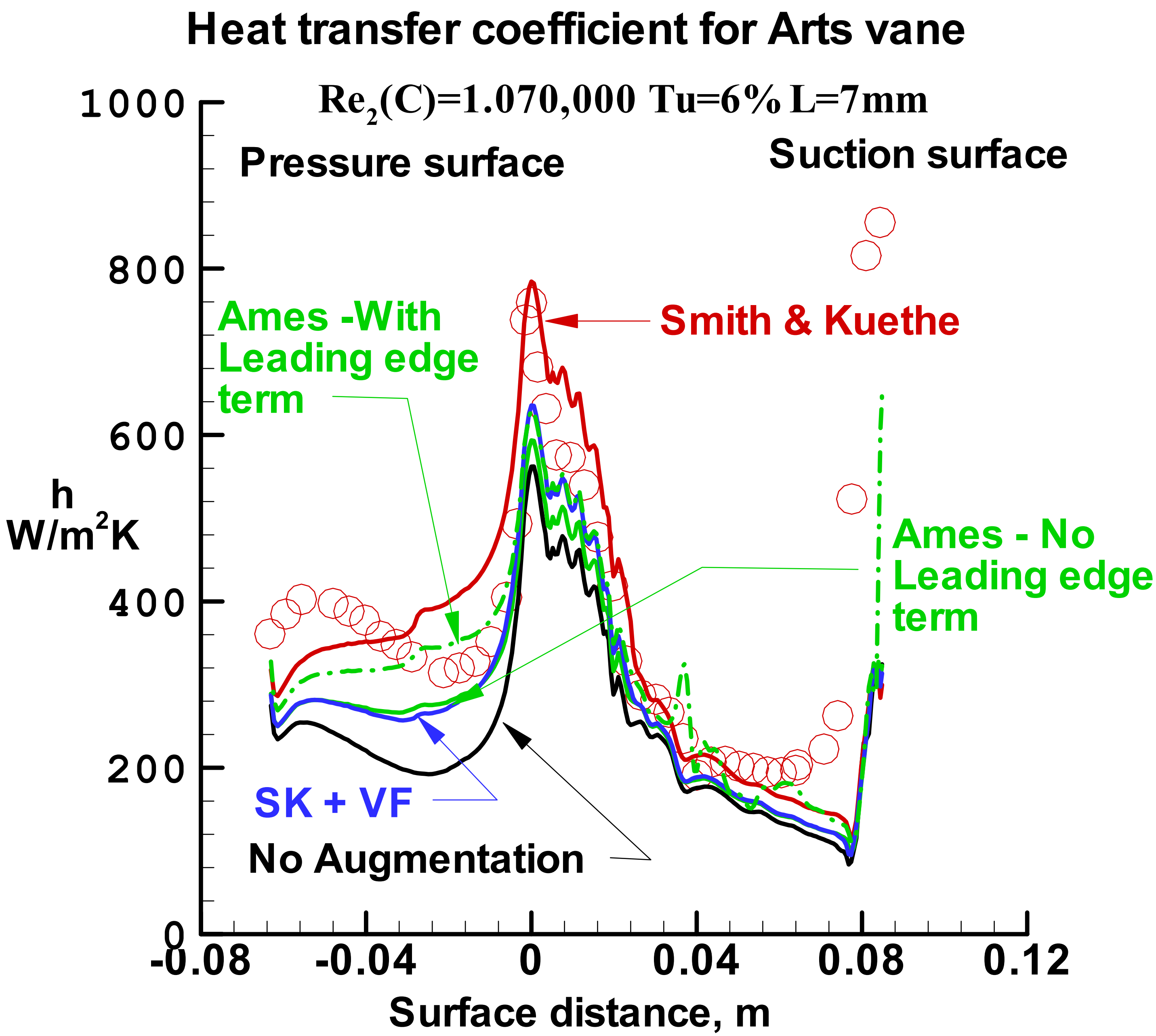
υ Lam
10^3
10^1
10^-1
10^-3
10^-5
10^-5
10^-4
10^-3
10^-2
10^-1
y/C

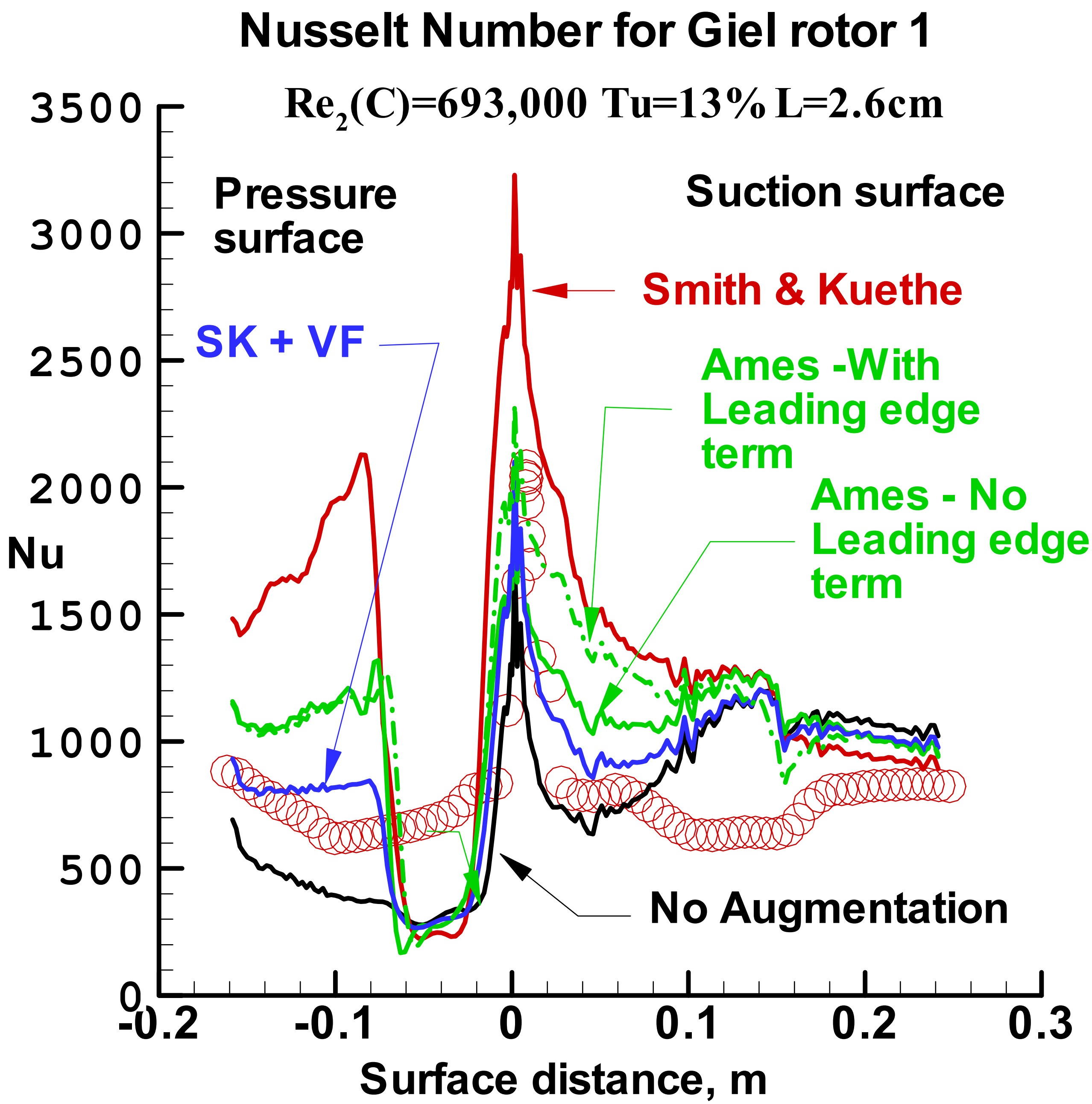
Heat transfer coefficient for Ames No. 1 vane




Stanton number for Ames No. 2 vane
Re2(C)=500,000 Tu=21% L=4.4cm
Pressure surface
Suction surface
Smith & Kuethe
Ames - No Leading edge term
Ames -With Leading edge term
SK + VF
No Augmentation
St X 1000
Surface distance, m
0
1
2
3
4
5
-0.6
-0.4
-0.2
0
0.2
0.4
0.6

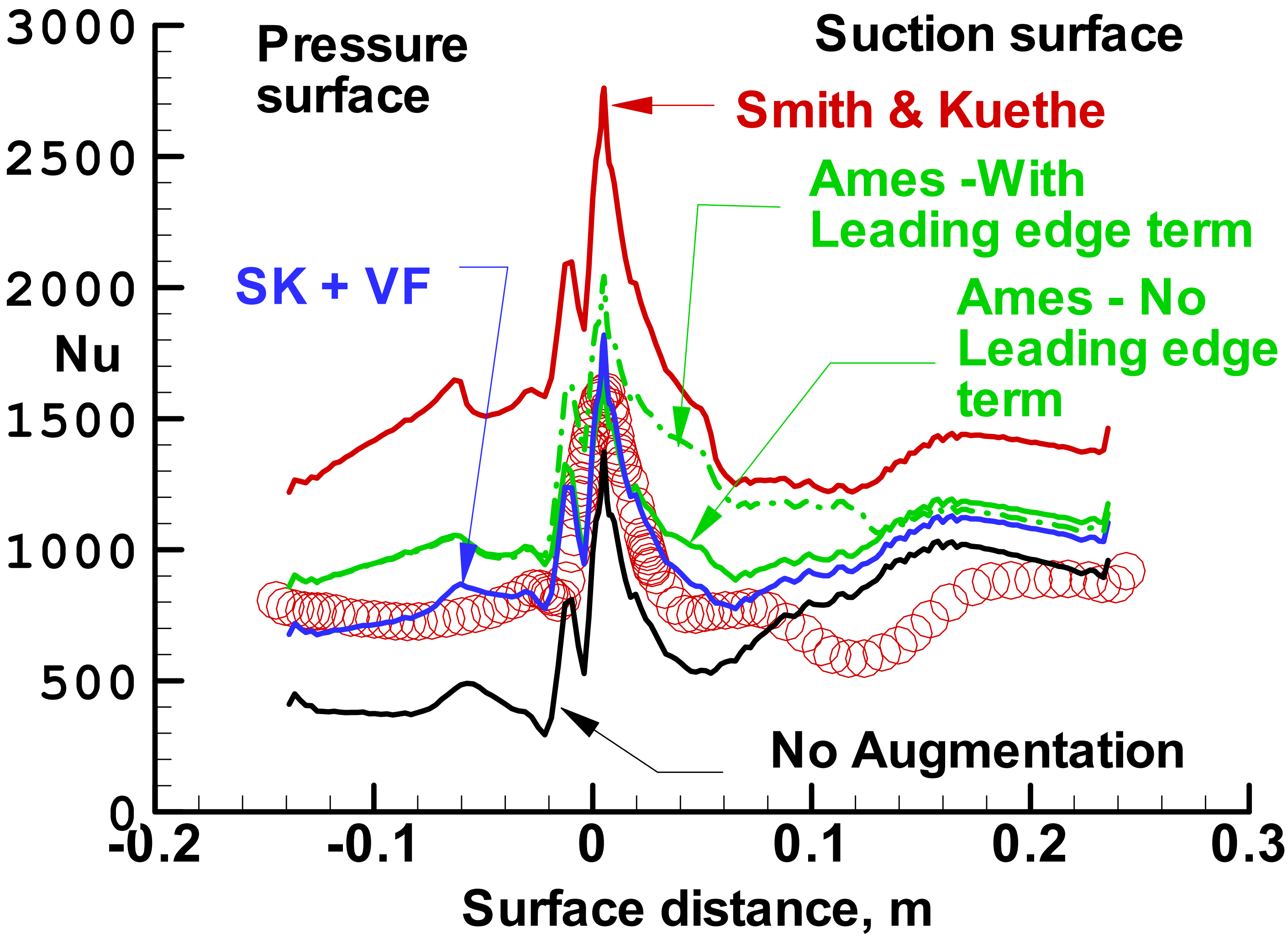

Heat transfer coefficient for Thole vane
Re$_2$(C)=1,070,000 Tu=20% L=5cm
Pressure surface
Suction surface
Ames -With Leading edge term
Smith & Kuethe
SK + VF
Ames - No Leading edge term
No Augmentation
h W/m^{2}K
120
100
80
60
40
20
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
Surface distance, m

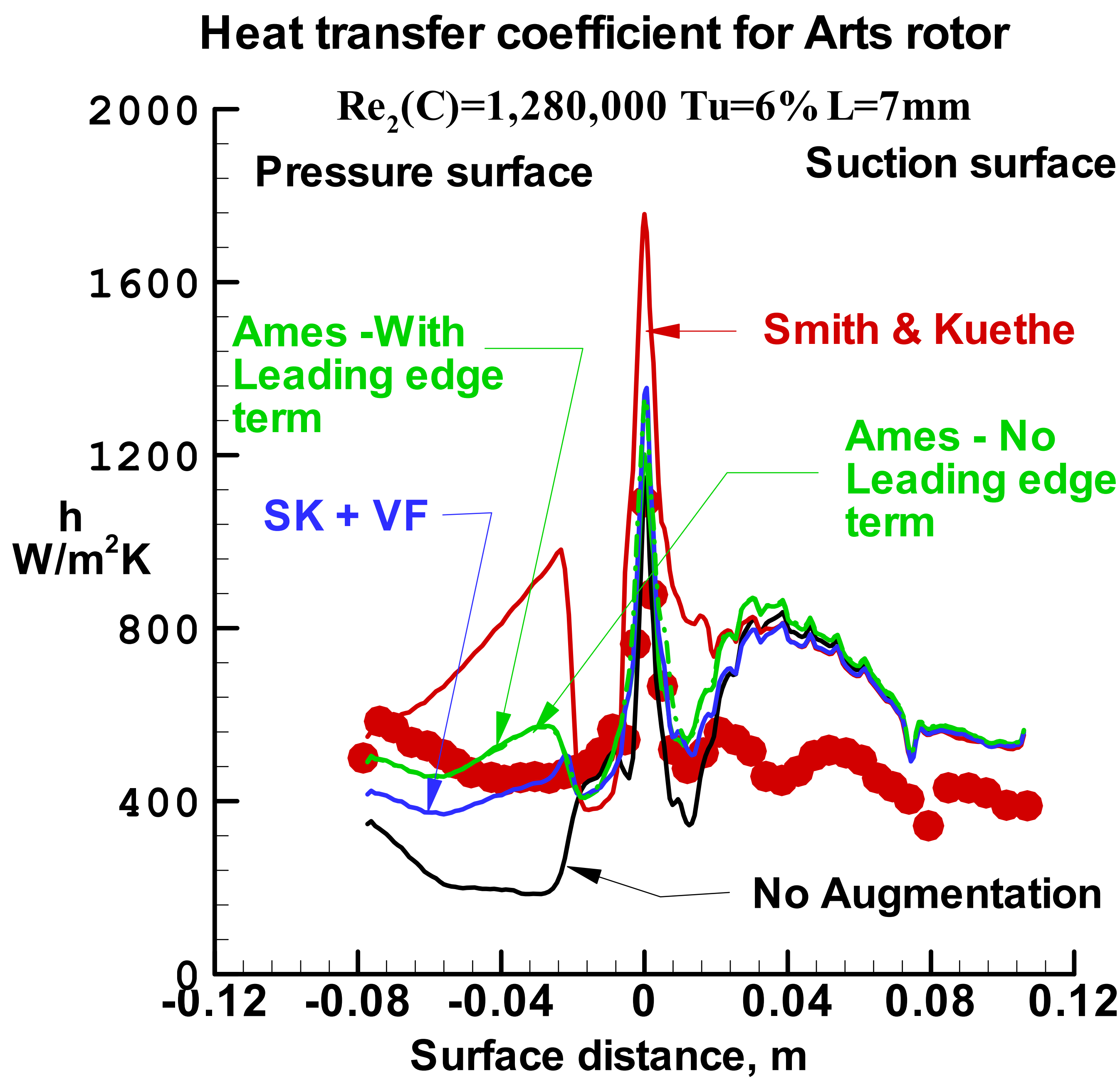

Heat transfer coefficient for Arts vane
Re2(C)=1.070,000 Tu=6% L=7mm
Pressure surface
Suction surface
h
W/m2K
Ames -With
Leading edge
term
Smith & Kuethe
Ames - No
Leading edge
term
SK + VF
No Augmentation
1000
800
600
400
200
0
-0.08
-0.04
0
0.04
0.08
0.12
Surface distance, m


Nusselt Number for Giel rotor 1
Re$_2$(C)=693,000 Tu=13% L=2.6cm
Pressure surface
Suction surface
Smith & Kuethe
SK + VF
Ames -With Leading edge term
Ames - No Leading edge term
No Augmentation
Nu
3500
3000
2500
2000
1500
1000
500
0
-0.2
-0.1
0
0.1
0.2
0.3
Surface distance, m

Nusselt Number for Giel rotor 2

$Re_2(C)=718{,}000$ Tu=13% L=2.6cm




Heat transfer coefficient for Arts rotor
Re$_2$(C)=1,280,000 Tu=6% L=7mm
Pressure surface
Suction surface
Ames -With Leading edge term
Smith & Kuethe
Ames - No Leading edge term
SK + VF
No Augmentation
h W/m^{2}K
2000
1600
1200
800
400
0
-0.12
-0.08
-0.04
0
0.04
0.08
0.12
Surface distance, m

Preliminary Conclusions

•Incorporating a model for turbulence effects improves agreement with data
•Ames's model without leading edge effect showed the most promise
•Smith & Kuethe recalibrated using Van Fossen's data showed similar results

Issues Identified

- Length scale variation with freestream velocity not examined
- Variation of start or length of transition with length scale not identified – May be important in favorable pressure gradients.